Spectral Estimation of Periodically Moving Part Modulation Based on AIDME Algorithm

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Abstract: The Periodicallg Moving Part Modulation (PMPM) for the moving parts in target provides important signatures for target recognition. However, most radars operate in multiple-target mode and can only get discontinuous clusters of the returned pulses, which makes it extremely difficult to extract PMPM signature from the echoes. This paper puts forward the Alternative Iteration Deconvolution based on Minimum Entropy criteria (AIDME) for spectral estimation of extended target's echoes, utilizing the special feature that the PMPM spectra usually have simple structures. Experimental results show that this method can effectively eliminate the severe influence caused by the convolution kernel and gain a satisfactory spectral estimation that approaches to the true spectrum.

Key words: moving part; modulation; deconvolution; spectral estimation

一种新的周期性运动部件调制谱估计方法. 冯孝斌, 黄培康, 肖志河. 中国航空学报(英文版), 2004, 17(3): 176-180.

摘 要: 目标内部运动部件对雷达回波产生的周期性运动部件调制(PMPM)为目标识别提供了丰富的特征信息。但由于大多数雷达均采用多目标工作方式, 因此, 通常情况下只能从雷达获得不连续的目标回波脉冲串, 这极大增加了根据目标回波频谱提取 PMPM 特征的难度。针对含 PMPM 目标回波频谱具有简单结构这一特点, 提出了基于最小熵准则的交替迭代反卷积方法(AIDME)用于扩展目标雷达回波频谱估计。结果表明: 与傅里叶谱分析方法相比, 该方法能够有效消除卷积核函数的不利影响, 获得逼近目标回波真实谱的良好谱估计结果。

关键词: 运动部件; 调制; 反卷积; 谱估计
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It is well known that the moving parts in target can induce the modulation of radar returns[1, 2]. These periodically moving parts, such as the compressor and turbine blades of a jet aircraft, the propeller blades, and the rotor and tail blades of a helicopter, will produce periodically moving part modulation (PMPM) on the total scattering signal of the target. Because there is obviously corresponding relationship between the PMPM spectral signature and the aircralf engine's characteristic, it is possible to extract the PMPM spectral signatures as important information for target recognition[3-6].

In order to obtain accurate spectral estimation of the target's returns, radar should operate on high pulse repetition frequency (PRF) and for long accumulation time. However, these two conditions usually cannot be satisfied, especially for most of the modern radars often operating in multiple-target mode. So the radar returns obtained from the same target are separated into discontinuous clusters of pulses, as shown in Fig. 1. Generally, the interval T_2 between the two adjacent illuminations of the radar on the same target is some dozens of milliseconds, and the duration T_1 of each illumination on the same target is no more than ten of milliseconds. If Fourier spectral analysis is usde on one cluster of pulses, the frequency resolution just is about one hundred Hertz. The spectra of such low resolution are disadvantageous to extract accurate PMPM spectral signature. This problem is generally solved by two kinds of methods. One is employing modern spectral estimation technique to improve the frequency resolution. However, limited by the obtainable data, the improvement of the

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spectral resolution is restricted by such kind of methods. The other one is using Fourier transform on several adjacent clusters of pulses returned from the same target. But it also has an obvious disadvantage as shown in the following. The radar target return $s(t)$ is equal to the product of the actual signal $s_0(t)$ with the kernel function $h(t)$. The corresponding spectra $S(f)$ of the known signal $s(t)$ can be represented as the convolution of the spectra $S_0(f)$ of the actual signal $s_0(t)$ with the the spectra $H(f)$ of $h(t)$. The convolution of $S_0(f)$ and $H(f)$ expands each PMPM spectral component into many discrete spectral lines and consequently degrades the spectral resolution. This makes it difficult to extract accurate PMPM spectral signature.

So, this paper presents a new method named Alternative Iteration Deconvolution based on Minimum Entropy criteria (AIDME) to attempt to solve this problem. The deconvolution method using minimum entropy criteria was first presented by Wiggins[7]. Its basic idea can be described as: if the actual signal is composed of several large spikes, the accurate estimation of the actual signal can be obtained by minimizing the entropy of the known signal that is a part of the actual signal. As a result of motination of this idea, the AIDME method uses alterative iteration deconvolution in time domain and in frequency domain and introduces minimum entropy criterion into the iteration procedure in frequency domain, according to the fact that the spectra containing PMPM components are composed of several isolated large spikes. Experimental results show that this method can effectively eliminate the severe influence caused by the convolution and gain a satisfactory spectral estimation which approaches to the true spectra.

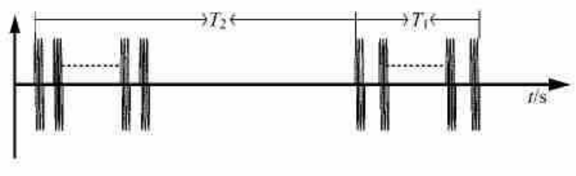


Fig. 1 Radar signal returned from the same target

2 Spectra of Extended Target's Echoes

The continuous echoes from the same target, namely actual signal, can be written as

$$s_0(t) = \alpha(t)e^{j\phi(t)}e^{j2\pi f_d t} = u(t)e^{j2\pi f_d t} \quad (1)$$

where f_d is the Doppler frequency caused by the radial movement of the target and the function of the corresponding factor $e^{j2\pi f_d t}$ just shifts the whole spectra of the target's echoes by a value of f_d and has on influence on spectral structures; $u(t)$ is the complex envelope of the target's returns; $a(t)$ and $\phi(t)$ are the amplitude and phase component of $u(t)$ respectively. The complex envelope $u(t)$ contains the PMPM components induced by the periodically moving parts. Generally, the PMPM components can be decomposed into amplitude modulation components and phase modulation components, and their spectra are constituted by a series of isolated spikes at the intervals of f_p, the value of which is determined by the product of blades number N_b and its revolution per second f_{rot}, viz, $f_p = H_b \cdot f_{rot}$. So, the $a(t)$ and $\phi(t)$ can be represented by different Fourier serieses[6] as

$$a(t) = \sum_{m=-\infty}^{\infty} a_m e^{j2\pi f_p m t} \quad (2)$$

$$\phi(t) = \sum_{l=0}^{\infty} b_l \sin(2\pi f_p l t + \varphi_l) \quad (3)$$

where a_m and b_l are Fourier coefficients; φ_l is the phase of the lth harmonic.

Because most of the radars operate in multiple-target mode, only a portion of the actual echoes is recorded. As similar as Eq. (1), the discontinuous echoes from the same target can be written as

$$s(t) = a(t)e^{j\phi(t)}e^{j2\pi f_d t}h(t) = s_0(t)h(t) \quad (4)$$

Just the $h(t)$ causes the degradation of the spectra of radar echoes. So, how to decrease the influence of $h(t)$ on $u(t)$ or $s_0(t)$ and obtain an optimal spectral estimation which approaches to the true spectra $S_0(f)$ is very important for extracting PMPM signature.

3 The AIDME Algorithm

As it is influenced by the periodically moving part modulation (PMPM), the spectra of the extended target's returns are composed of a series of isolated spikes, and most of the signal's energy is concentrated at several finite spikes. The entropy of the spectra can just express this characteristic of the spectra. Entropy depicts the randomness of the described signal. The more random or indefinite the signal is, the larger the entropy is and vice versa. For the spectra of extended target's returns, the more concentrative the energy is and the less the spectral components are and the simpler the spectral structure is, and the smaller the entropy of the spectra is. So, according to the priori information that the spectra containing PMPM components are composed of several large spikes, the unknown parts of the actual echoes can be restored by minimizing the entropy of the spectra of the known echoes, and then the spectral estimation can be obtained. As it is able to expect, the spectral estimation obtained by this method will most approach to the spectra $S_0(f)$ of the actual returns. This is because the spectral estimation is obtained on the basis of completely and exactly utilizing the signal's priori information. This is just the essential thinking of the AIDME algorithm presented in this paper.

According to Eq. (4), the sampling discontinuous echoes namely known signal can be written as

$$s(n)=\begin{cases} s_0(t)\sum_{l_2=0}^{L_2-1}\sum_{l_1=0}^{L_1-1}\delta(t-l_1\Delta t-l_1T_2) & n=l_2L_0+l_1 \\ 0 & \text{Other} \end{cases} \tag{5}$$

where $\delta(\cdot)$ is Dirac function; Δt is the radar pulse repetition period; L_1 is the recorded sample number of the echoes in each irradiation duration T_1; T_2 is the interval of the adjacent radar irradiations on the same target which is equal to the time in that radar continuously transmits or receives L_0 pulses; L_2 is the number of the clusters to be analyzed. So, the total length of $s(n)$ is $N = L_2L_0$. The AIDME algorithm can be divided into the following steps:

(1) First, let $i= 0$, and initialize the spectral series $S_i(k)$.

(2) Use inverse Fourier transform on $S_i(k)$, and obtain the estimation $s_i(n)$ of the actual signal.

(3) According to the known signal $s(n)$, the estimation $s_i(n)$ of the actual signal is revised by

$$s_{i+1}(n)=\begin{cases} s(n) & n=l_2\cdot L_0+l_1 \\ s_i(n) & \text{Other} \end{cases}$$

(4) Using Fourier transform on $s_{i+1}(n)$, the spectral estimation $S_{i+1}(k)$ of the actual signal can be obtained.

(5) The spectral estimation $S_{i+1}(k)$ of the actual signal is revised according to the minimum entropy criterion. The objective function is

$$J=-\sum_{j=0}^{N-1}p_j\log p_j \qquad j=0,1,2,\cdots,N-1,$$

where $p_j=\dfrac{|S_{i+1}(j)|}{\sum_{\eta=0}^{N-1}|S_{i+1}(\eta)|^2}$. The iterative search procedure is based on gradient method. That is

$$S_{i+2}(k)=S_{i+1}(k)-\mu\cdot\nabla J \qquad k=0,1,\cdots,N-1,$$

where ∇J is the gradient of the objective function J; and μ is the iterative step.

(6) Calculate the similar coefficient $r_{i+2,i}$ of $S_i(k)$ and $S_{i+2,i}(k)$, if $r_{i+2,i}\geqslant\varepsilon$, then the iteration is terminated, where ε infinitely approaches and always is smaller than 1, and $S_{i+2}(k)$ is the final spectral estimation of the actual signal; otherwise, let $i=i+2$, and go back the second step to continue the iteration procedure.

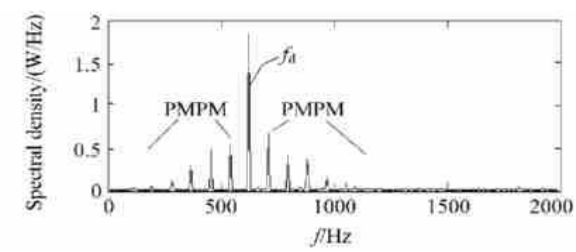
It should be noted that there are many criterions to terminate the iteration procedure, for example, the iteration times can be specified according to the statistical observation.

4 Experimental Results and Analysis

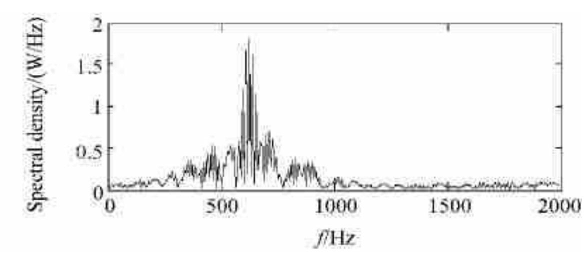
To verify the validity of the AIDME algorithm, the following tests are carried out. If radar pulse repetition period Δt is 0.5ms, the duration of each irradiation T_1 is 16ms and the interval of adjacent irradiation T_2 is 64ms, correspondingly, L_1 is 32 and L_0 is 128. And the number of the clusters L_2 is appointed to be 3. The target's Doppler frequency f_d is 8625Hz. The number of the engine blades N_b is 4, and rotation rate f_{rot} is 21.48 rev/

s. Let $m = \{-3, -2, -1, 0, 1, 2, 3\}$, then $a_m = \{0.2, 0.3, 2.0, 0.5, 0.4, 0.3\}$. Let $l = \{0, 1, 2, 3\}$, then $b_l = \{1.5, 0.4, 0.3, 0.2\}$. φ_l is random given and $\varphi_l \in [0, 2\pi]$. $n_0(t)$ is additive Gaussian white noise with zero means, and its standard deviation is determined by the signal power and the Signal Noise Ratio (SNR). The processing results are shown in Fig. 2. Fig. 2(a) shows the spectra $S_0(f)$ of the actual signal $s_0(t)$, and Fig. 2(b) shows the spectral estimation of the known signal $s(t)$ based on periodogram method. The spectral estimation $S_{AIDME}(f)$ of $s(t)$ based on AIDME algorithm is shown in Fig. 2(c). Compared with Fig. 2(a), Fig. 2(b) shows the distortion effect of the convolution kernel $H(f)$ on the $S_0(f)$. Influenced by $H(f)$, the eight visible PMPM components contained in $S_0(f)$ become a number of discrete spectral lines and undistinguishable with each other. Fig. 2(c) shows that the AIDME algorithm not only can effectively restrain the redundant spectral lines introduced by $H(f)$ and obtain high frequency resolution, but also can completely remain the actual PMPM spectral lines, and the positions of them on the frequency axis are consistent with the actual positions.

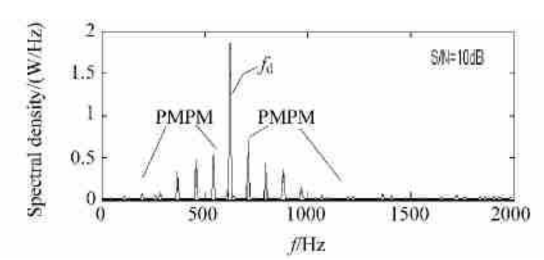
The AIDME algorithm is also tested by measured data. Because the measured data are recorded by single-target radar, the continuous echoes from a same target namely actual signal $\hat{s}_0(t)$ are known. And then the discontinuous echoes $\hat{s}(t)$ namely known signal can be easily obtained according to $\hat{s}_0(t)$. Fig. 3 shows the processing results of the measured data of a jet airplane. The spectra $\hat{S}_0(f)$ of the actual signal $\hat{s}_0(t)$ are shown in Fig. 3(a), the spectral estimation $\hat{S}(f)$ of the known signal $\hat{s}(t)$ based on periodogram method is shown in Fig. 3(b), and the spectral estimation $\hat{S}_{AIDME}(f)$ of $\hat{s}(t)$ based on AIDME algorithm is



(a) The spectra $S_0(f)$ of $s_0(t)$

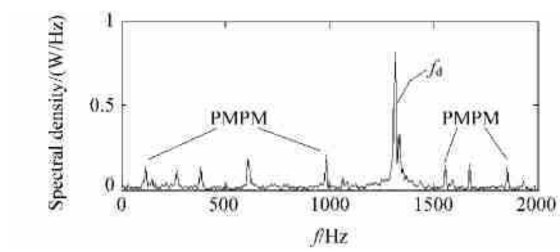


(b) The spectral estimation $S(f)$ of $s(t)$ based on periodogram

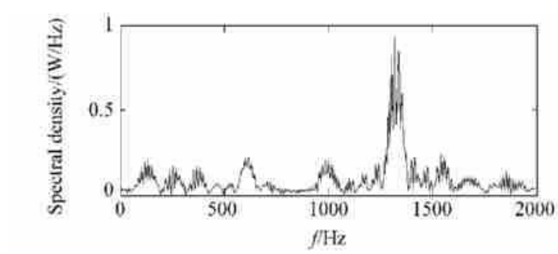


(c) The spectral estimation $S_{AIDME}(f)$ of $s(t)$ based on AIDME algorithm

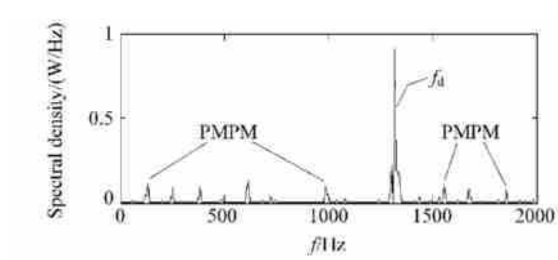
Fig. 2 The results based on simulated data



(a) The spectra $\hat{S}_0(f)$ of $\hat{s}_0(t)$

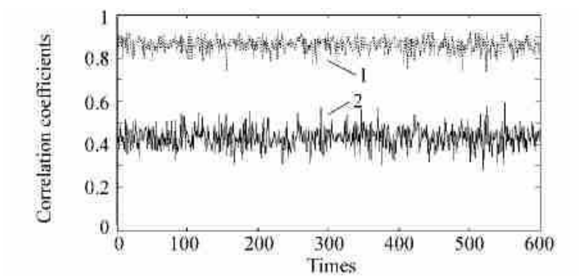


(b) The spectral estimation $\hat{S}(f)$ of $\hat{s}(t)$ based on periodogram



(c) The spectral estimation $\hat{S}_{AIDME}(f)$ of $\hat{s}(t)$ based on AIDME algorithm.

Fig. 3 The results based on measured data shown in Fig. 3(c). The results show that the AIDME algorithm can evidently improve the estimation accuracy of the PMPM spectral components by contrast with the periodogram method. Fig. 4 shows the correlation coefficients of $S(f)$ and $S_0(f)$, and the correlation coefficients of $S_{AIDME}(f)$ and $S_0(f)$ varying with the statistical times. The 600 statistical results show that the mean correlation coefficient of $S_{AIDME}(f)$ and $S_0(f)$ is 0.87, while the mean correlation coefficient of $S(f)$ and $S_0(f)$ is only 0.43.



Curve 1 is the correlation coefficients of $S_{AIDME}(f)$ and $S_0(f)$. Curve 2 is the correlation coefficients of $S(f)$ and $S_0(f)$.

Fig. 4 The correlation coefficients vs. statistical times

So, the processing results of both the simulated data and the measured data show that the AIDME algorithm can effectively reduce the disadvantageous influence on spectral estimation caused by the discontinuous irradiation, and obtain the accurate PMPM spectral estimation.

5 Conclusions

This paper presents an alternative iteration deconvolution algorithm namely AIDME in order to resolve the problem of how to obtain the accurate PMPM spectra under the conditions of some of the radar returns unknown. By alternative iteration in time domain and in frequency domain and introducing the minimum entropy criterion into the iteration procedure in frequency domain, the AIDME algorithm can effectively reduce the distorting influence of the convolution kernel on the PMPM spectral components. The experimental results show that the AIDME algorithm not only can effectively restrain the redundant spectral lines, but also can completely remain the actual PMPM spectral components.

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